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Soil-Bentonite Permeability and Compatibility Testing
Slurry Wall Construction
Former Acid Plant Sediment Drying Area

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Report
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Slurry Wall Construction
Former Acid Plant Sediment Drying Area
Asarco Project, East Helena, MT

Introduction

This report presents the results of laboratory tests performed on soil-bentonite slurry wall backfill materials for the installation of a groundwater cutoff wall at the Former Acid Plant Sediment Drying Area at the Asarco Smelter Facility at East Helena, MT (Site). The work described in this report was completed in accordance with our agreement with Shaw Environment Inc of Concord, CA for PO No. 220561 OP.

In order to be effective, a slurry cutoff wall must be compatible with the local groundwater and provide a low permeability barrier to that groundwater. The Site is known to be contaminated with high levels of arsenic that may negatively affect bentonite clay, the principal additive in most slurry walls. Accordingly, this laboratory study was completed to determine the compatibility of the slurry wall materials and the optimum amount of additives to use in the slurry wall backfill to provide a groundwater barrier with a hydraulic conductivity (or permeability) of 1×10^{-7} centimeters per second (cm/sec) or less.

Due to the uncertainty in compatibility and the need to act quickly, two types of slurry wall materials were considered; soil-bentonite (SB), and soil-cement-bentonite (SCB). SB slurry walls generally provides the lowest permeability, while SCB is slightly more permeable (typically, less than 5×10^{-7} cm/sec), but sometimes more resistant to some contaminates. SB is preferred due to its lower permeability and lower cost, but SCB was considered as a backup material, if necessary.

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Scope of Testing Program

The scope of the testing program includes a phased program as follows:

1. Field Phase: Retrieve representative samples of the Site soils, local borrow soil, local mix water, and Site groundwater. This phase was completed by Asarco and samples were sent directly to our laboratory for analysis and testing.
2. Characterize the Site materials. Tests were performed on the Site materials for index properties to identify potential materials for developing bentonite slurry and backfill mixtures.
3. Perform index tests for compatibility with commercial clays (e.g., bentonite) and the Site groundwater. The objective of these tests is to quickly eliminate any additives which indicate any potential incompatibility with the Site groundwater.
4. Perform index tests for compatibility with cement grouts (e.g., cement-bentonite) and the Site groundwater. The objective of these tests is to eliminate any grouts which demonstrate any potential incompatibility with the groundwater. If phase 3 and 4 are both successful, continue the laboratory testing program with only SB materials.
5. Formulate and test a number of trial backfill mixtures and test these mixtures for permeability to tap water. The objective of these tests is to develop a mixture with a low permeability using the materials developed in the previous phases.
6. Formulate and test the best backfill mixtures from phase 5 for permeability to the Site groundwater. In order to fully document our success, the mixtures tested in this phase were subjected to at least 2 pore volumes of permeation with the Site groundwater. It has been our experience that this phased approach guarantees a successful mixture.

Laboratory

Laboratory testing was completed by Advanced Terra Testing (ATT) of Lakewood, CO under the direction of Steve Day of Geo-Solutions. ATT is fully qualified, licensed and experienced to perform all type of soil and rock testing. Mr. Day and ATT have worked together on this type of testing for more than a decade. Their combined experience includes major groundwater barrier projects for Rocky Mountain Arsenal Chemical Warfare Materials Disposal sites, Rocky Flats Nuclear Weapons site, Superfund sites, and many other similar sites.

Standards and Methods

The standards and methods to be employed in this report are listed in Table 1.

Table 1: Laboratory Standards and Methods

Test	Standard or Reference
Grainsize	ASTM D422
Fines Content	ASTM D1140
Atterberg Limits	ASTM D4318
Moisture Content	ASTM D2216
Soil Classification (USCS)	ASTM D2487
Water Quality (ph, Hardness, TDS)	Hach Test or equal
Slurry Preparation	API 13A mod.
Soil-Cement sample preparation	ASTM D4832 mod.
Slump (mini-slump method)	ASTM D143 mod.
Viscosity and Density	API RP 13B-1
Filtrate, pH, and temperature	API RP 13B-1
Bleed and Set	ASTM C940 mod.
Penetration Resistance	ASTM D1558 mod.
Hydraulic Conductivity (permeability)	ASTM D5084
Hydraulic Conductivity: Long Term	ASTM D7100 mod.
Pan-Set	CRA, June 1991
Slake / Immersion	ASTM C267 & D4644 mod.
Chemical Desiccation	Alter et. al. 1984 mod.
Sedimentation / Flocculation	Ryan 1987
Long-term Filtrate w/ Leachate	D'Appolonia 1980

Characterization of Site Resources

The available Site resources include the slurry mixing water (Upper Lake water), potential trench spoils, and CAMU borrow soils. An area east of the proposed Corrective Action Management Unit (CAMU) Phase 2 Cell was utilized as the clean onsite borrow source. The borrow source soils are commonly referred to as the "CAMU borrow soils" in the bench scale laboratory studies. These materials were utilized as the basic materials for the slurry wall backfill and bentonite slurry. Based on previous experience on Site, a considerable volume (about 50%) of cobbles, boulders, and debris was expected is the trench spoils that would not be suitable for use in the slurry wall backfill. The unsuitable trench spoil was intended to be replaced with the CAMU borrow soils to make a 50:50 mixture of soil for the slurry wall backfill. The properties of these soils are summarized in Table 2.

Table 2: Soil Properties

Property	Composite Soils	CAMU Borrow Soils	50% Soils + 50% CAMU
Water Content (%)	10.7	9.6	21.6
Fines (%<#200 sieve)	25	23	22
Organic Content (%)	--	--	1.8
Liquid Limit (%)	--	--	41
Plastic Limit (%)	--	--	21
Plastic Index (%)	--	--	20
Classification (USCS)	--	--	CL

In order to make the slurry wall backfill mixture representative, yet somewhat conservative, only certain soils were included from materials of the exploratory borings. All rocks greater than 0.5 inches were excluded to better model proposed field procedures (where as soils greater than 3 inches were excluded) and to ensure accurate testing in accordance with ASTM standards. In addition, all soils which appeared to be clay or clayey, including key soils (volcanic tuff), were excluded. These steps resulted in a backfill mixture with the fines content of about 22%. The amounts of fines in the soils are generally considered adequate for either a low permeability SB or SCB mixture. Finally, water was added to the 50:50 mixture in an attempt to restore the soils to a moisture content more typical of soils found beneath the groundwater table. The added water doubled the water content of the composite soils from about 10% to about 20%. A picture of the 50:50 backfill mixture and CAMU borrow soils are shown below.

Figure 1A: Backfill Mixture Soils

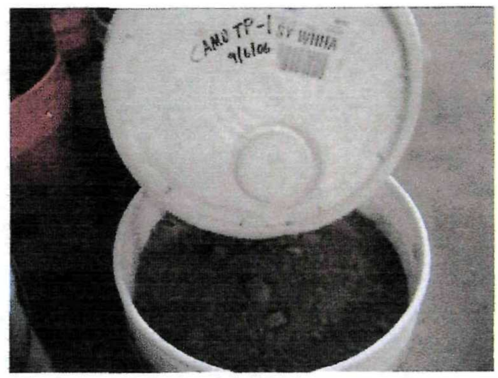

Figure 1B: CAMU Borrow Soils

The Upper Lake and groundwater from the Site were also tested for index properties. The properties of the waters are shown in Table 3.

Table 3: Water Properties

Property	Upper Lake Water	Groundwater (APSD-3)
pH	7.4	7
Hardness (ppm)	144	375
TDS (ppm)	195	750

The properties of the Upper Lake water appeared to be usable for the making a bentonite slurry. The Site groundwater is harder and contains more suspended solids.

Clay Compatibility via Index Tests

Three commercial clays were subjected to compatibility testing with the Site groundwater: API bentonite (Fed Jel 90), salt resistant bentonite (SR bentonite or SW 101), and attapulgite clay (Florigel H-Y). The API bentonite is representative of the most common slurry wall material. SW 101 is a specially treated bentonite clay, most often used in off-shore drilling and typically mixed with salt water. Attapulgite is a clay from northern Florida that does not swell like bentonite and has been used on some other severely contaminated sites and can be mixed with salt water. The properties of 6% clay slurries made with Upper Lake water are shown in Table 4.

Table 4: Slurry Properties

Property	Bentonite	SR Bentonite	Attapulgite
Viscosity (MF seconds)	40	>180	26
Filtrate (ml/ 30 min.)	17	8.3	79
Density (pcf)	65	65	65
pH	8.5	9	9.4

Index-type compatibility tests were performed with the clay slurries to detect potential gross incompatibility or other reaction between the slurries and contaminated waters. The tests were performed by first using the slurries made with the Upper Lake water and a clay and subjecting it to different tests with the Site groundwater.

Sedimentation/flocculation tests were performed to help determine whether the clay will fall out of suspension in the presence of the groundwater during construction. Slurries were made with each of the clays and diluted 1:1 with tap water and Site groundwater. The slurries were poured into graduate cylinders and then observed for at least 7 days. Comparisons were made between slurries diluted with tap water and groundwater.

The results of the sedimentation tests are shown in the photographs in Figure 2.

Figure 2: Sedimentation/Flocculation Test Results

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The best results were demonstrated by the Fed Jel 90 (API-type) bentonite. There was no indication of any sedimentation or flocculation with the API bentonite. The attapulgite clay appeared to demonstrate the worst results, but this is may be due to in part to problems with producing adequate mixing by the laboratory. Attapulgite requires very aggressive mixing. There appears to be a minor sedimentation with the SW 101 in tap water.

Chemical desiccation tests were performed to help determine if the groundwater affects the chemical structure of the clay. Slurries were made with each of the clays, as previously described and diluted at a 1:1 with tap and Site groundwater. These mixtures were poured onto glass plates and allowed to dry. The cracking pattern of the dried slurry is then examined for any unusual patterns. Comparisons were made between slurries diluted with tap water and Site groundwater.

The results of the chemical desiccation test are shown in the photographs of Figure 3.

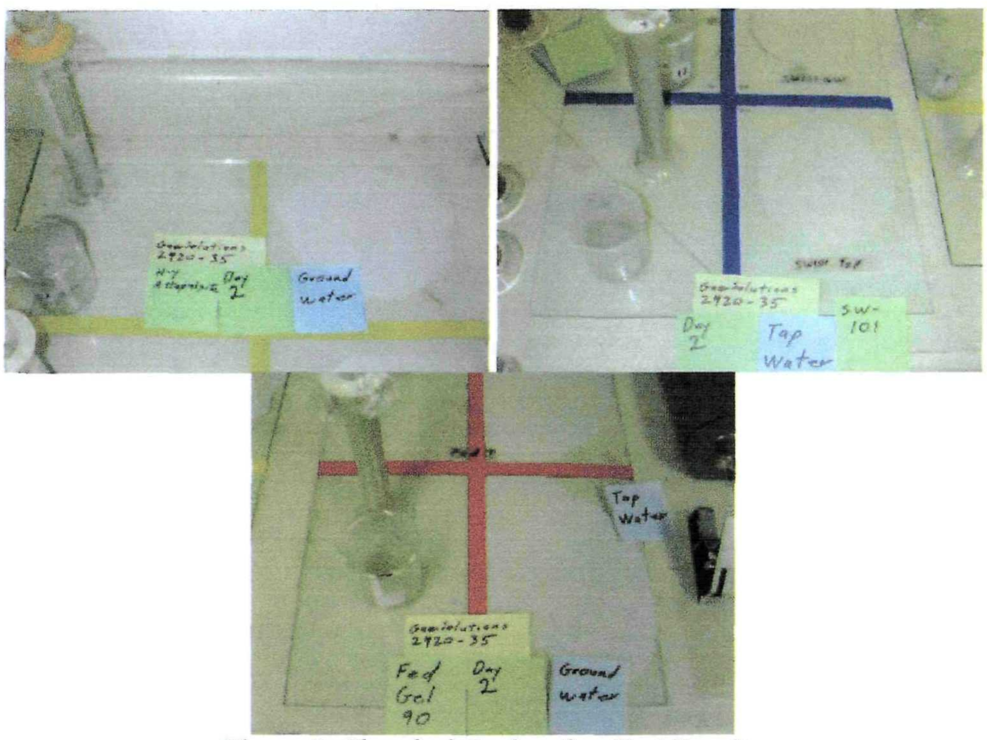
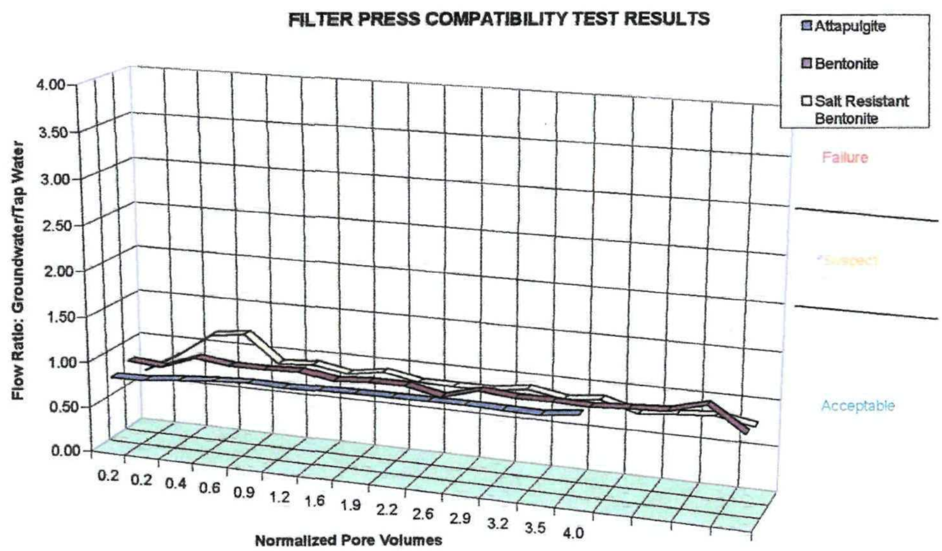


Figure 3: Chemical Desiccation Test Results

There was no cracking or other indications of chemical desiccation in any of the tests. All of the clays performed similarly.

Filter press permeability tests were performed to help determine if the groundwater will degrade the filter cake of the commercial clay. The test was performed by first completing two standard filtrate tests (30 minutes at 100 psi) with each of the clay slurries. Next, the supernate from each test was decanted and the two cells (with filter cakes still intact) were refilled one with tap water and one with groundwater. The test cells were again pressurized (at 100 psi) and the test continued for about 3 hours while the flow rate of the waters through the two filter cakes is monitored. The flow rates can be compared as the ratio of the filtrate of the Site groundwater to the filtrate of the tap water verses the pore volumes of flow. A ratio where the Site groundwater flows through the filter cake twice as fast as tap water flow through the filter cake is considered potentially incompatible.

The results of the modified filter press tests are presented in the graph, below.



	0.2	0.2	0.4	0.6	0.9	1.2	1.6	1.9	2.2	2.6	2.9	3.2	3.5	4.0				
Attapulgite	0.82	0.83	0.87	0.90	0.92	0.91	0.92	0.93	0.93	0.94	0.94	0.93	0.92	0.97				
Bentonite	0.89	0.86	1.00	0.96	0.96	0.97	0.91	0.94	0.94	0.86	0.97	0.94	0.94	0.93	0.95	0.98	1.08	0.82
Salt Resistant Bentonite	0.67	0.88	1.14	1.20	0.91	0.93	0.87	0.93	0.86	0.86	0.86	0.92	0.85	0.88	0.78	0.81	0.85	0.77

Figure 4: Filter Press Compatibility Test

The ratio of flow with groundwater and tap water are all similar and acceptable for all three clays. Therefore, there is no indication of any incompatibility in the modified filter press tests.

Based on these results, API-type bentonite is compatible with the site groundwater and selected for further testing in phase 5.

<u>Grout Compatibility via Index Tests</u>

Three different grout mixtures were formulated and subjected to compatibility testing with the groundwater: PC1 consists of a cement (PC)-bentonite grout, PC2 consists of a blast furnace slag (BFS)-cement-bentonite grout, and PC3 consists of a blast furnace slag-attapulgite grout. The properties of grouts when mixed with Upper Lake water are shown in Table 5.

Table 5: Grout Properties

Trial Mix No.	REAGENT TYPE	REAGENT/WATER (%)	Apparent Viscosity (cP)	Grout Density (pcf)	Grout Bleed (%)	Grout pH (units)	Penetration Resistance (tsf-day 3)
PC1	PC/Bentonite	0.2 / 0.05	42	72.4	0	12.0	0.1
PC2	BFS/PC/ Bentonite	0.165 / 0.55 / 0.025	13	71.8	5	12.0	0.4
PC3	BFS/ Attapugite	0.12 / 0.06	2.5	69.3	55	10.0	1.9

Index-type compatibility tests were performed with the grouts to detect potential gross incompatibility or reaction between the cement grouts and Site groundwater. Two different index-type compatibility tests were performed with the cement grouts and the Site groundwater. In the Pan test, a fluid grout was poured into a pan filled with either Site groundwater or tap water. The grouts are tested for penetration resistance as they set and harden over time, under the waters, to detect any observable differences in the setting process due to the different waters.

The results from the Pan test produced considerable differences between the setting time of the three grouts, but only minor differences between identical grouts immersed in tap water and Site groundwater. No incompatibilities were observed in the pan test.

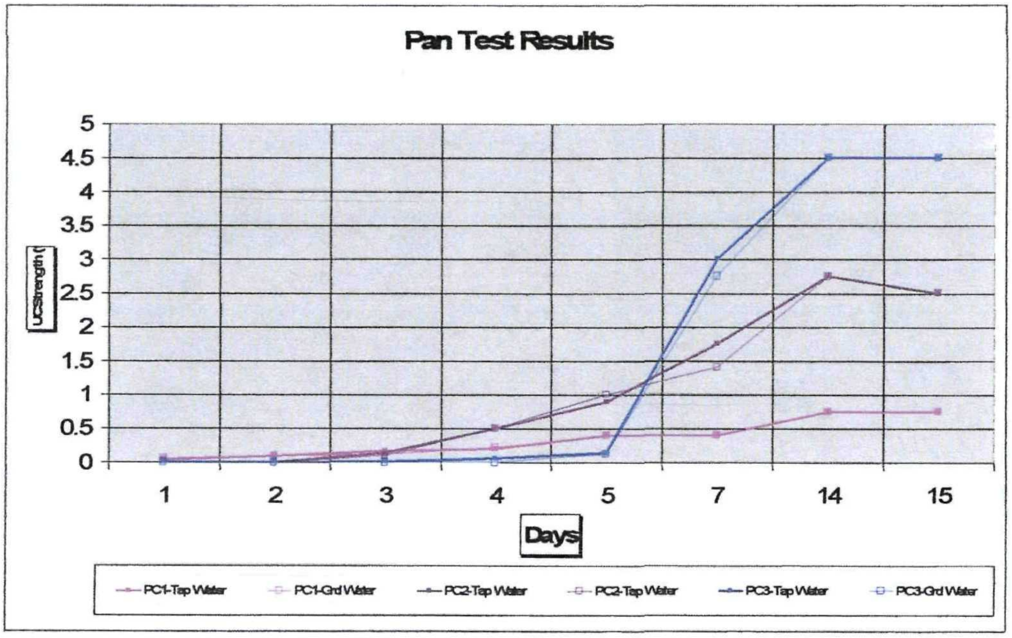


Figure 5: Pan Test Results

In the Slake test, hardened 2 x 4 inch cylinders of grout were allowed to cure for one month under standard conditions, and then immersed in Site groundwater and tap water. The cylinders were soaked for one month, then removed, dimensioned and weighed to detect any changes in density due to immersion in the different waters. Photographs of the tests are shown in Figure 6.

Figure 6: Slake Tests

Typically, a change in density of more than 20% indicates a potential in compatibility. None of the grouts tested lost or gained more than about 4% in density (to tap water) and therefore, no incompatibility was observed. The results of the tests are summarized in Table 6.

Table 6: Slake Test Results

Mix No.	Water	Change in Density (Δ %)
PC1	Tap	-4.17
PC1	Ground	0.19
PC2	Tap	-3.11
PC2	Ground	-0.84
PC3	Tap	-0.92
PC3	Ground	0.39

There was no obvious incompatibility or obvious reaction between the hardened grouts and the Site groundwater. All of the grouts performed adequately in all of the tests and no incompatibilities were observed in either index test. Since the bentonite clays also performed without indication of an incompatibility, grout testing was discontinued and the remaining portions of the laboratory test program focused producing an acceptable soil-bentonite mixture.

Phase 5 Testing – Soil-Bentonite Mixtures

In phase 5, five soil-bentonite mixtures were formulated and tested for water content, density, workability, and permeability to water. Four SB mixtures were made by mixing the CAMU borrow soils and composite soils in 50:50 proportions and then blending in the desired amounts of dry bentonite and slurry bentonite. A fifth mixture was made with only CAMU borrow soils and bentonite to serve as a contingency mixture, should the 50:50 mixtures prove to be unsuitable. Slurry bentonite was added to the soils until a slump of 4 to 6 inches was recorded. The proportions and properties of the mixtures are listed in Table 7.

Table 7: SB Proportions and Properties

Mix No.	Soils	Dry Bentonite Added	Slurry Bentonite Added	Total Bentonite Added	Slump	Density
	(50/50 mix)	(%)	(%)	(%)	(inches)	(pcf)
1	CAMU / Composite	0%	1.1%	1.1%	5.5	119
2	CAMU / Composite	1%	1.3%	2.3%	5.0	119
3	CAMU / Composite	2.5%	1.5%	4.0%	4.5	115
4	CAMU / Composite	5%	2.0%	7.0%	5.0	112
5	CAMU	1%	1.8%	2.8%	4.5	123

The mixtures of CAMU borrow and composite soils with bentonite produced an acceptable SB slurry wall mixture. The slump and density of the mixtures are typical of SB. The amount of slurry bentonite added, is slightly higher than typical. This is probably due to the tendency of the dry and silty CAMU borrow soils to absorb more moisture as slurry.

The SB mixtures were placed in flexible wall permeameters and tested at an effective stress of 10 psi and a hydraulic gradient less than 30 and permeated with water in accordance with ASTM D5084, Method D (flow pump). The results of permeability tests on the SB mixtures are shown in Table 8.

Table 8: SB Permeability Test Results

Mix No.	Soils	Bentonite Added	Density	Permeability
	(50:50 mixture)	(%)	(pcf)	(cm/sec)
1	CAMU / Composite	1.1%	110	4.6×10^{-8}
2	CAMU / Composite	2.3%	113	3.1×10^{-8}
3	CAMU / Composite	4.0%	110	2.2×10^{-8}
4	CAMU / Composite	7.0%	107	1.4×10^{-8}
5	CAMU	2.8%	108	2.1×10^{-8}

All of the mixtures easily meet the standard of less than 1×10^{-7} cm/sec. The results of the tests on the SB mixtures 1 through 4 are portrayed in the Figure 7.

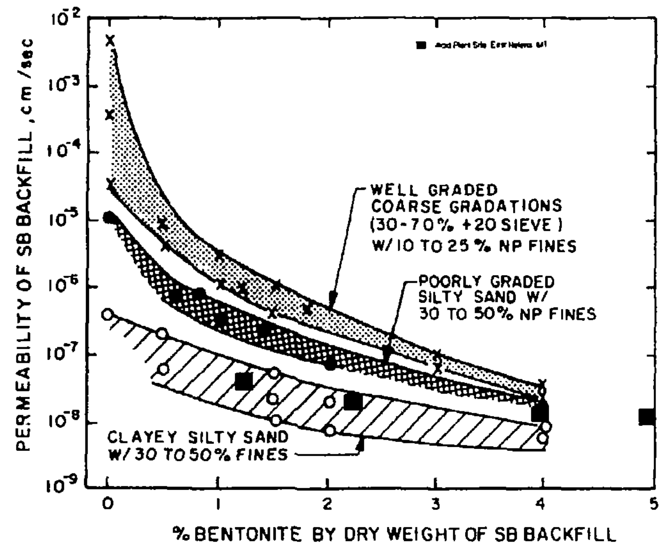


Figure 7: Permeability Test Results

From the graph it is apparent that the optimum amount of bentonite added is in the range of 2 to 3% or similar to mixtures 2 and 3. Adding extra bentonite did not seem to produce a meaningful improvement in impermeability. Therefore, the additional long-term permeability testing was performed with SB mixture 2.

Long-Term Permeability Testing

Flexible wall permeability tests were performed on the SB mixture 2 using Site groundwater as the permeant. The goal of the test was to pass at least two pore volumes of groundwater through the specimen to ensure steady state flow (physical and chemical steady state) and determine when to terminate the test. The state of the art in laboratory determinations of barrier compatibility is the flexible wall permeability test. In this test, the specimen is permeated with groundwater for an extended period to model the long term performance of the barrier. The amount of groundwater forced through the specimen is tracked in pore volumes of flow. A pore volume is the volume of voids (non-solids) in a specimen. For most sites (with hydraulic gradient < 1, barrier thickness = 3 ft, and barrier permeability = 1 x 10^{-8} cm/sec), each pore volume represents about 100 years of performance. It should be noted that for a barrier with a permeability of 1 x 10^{-7} cm/sec, a pore volume represents 10 years of performance.

The long-term permeability test was continued for 15 weeks or 100 days and succeeded in passing 2.4 pore volumes of Site groundwater through the test specimen. The permeability of the SB test specimen started at 3 x 10^{-8} cm/sec in the flow pump permeability test with water. When the test was switched to the constant head test with Site groundwater as the permeant, the permeability rose to about 5 x 10^{-8} cm/sec, as a result of the different apparatus and method, and remained near that value throughout the test. Measurements of permeability were taken about 2 to 3 times per week throughout the test. The final permeability of the specimen was 4 x 10^{-8} cm/sec. Since the pore volume of the sample cannot be determined until the test is dissembled, the pore volume was estimated to determine when to terminate the test. The chart below shows the permeability of the SB mixture 2 trend verses pore volumes in the long-term test.

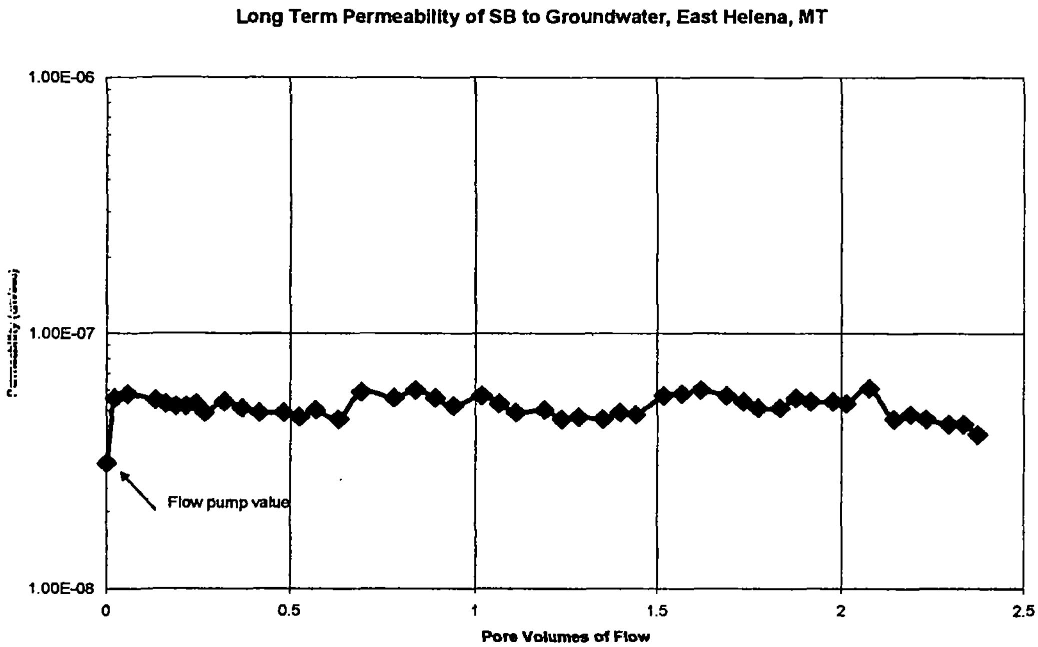


Figure 8: Long Term Permeability Test Result

There was limited variability in the permeability of SB mixture 2 during the test. The highest recorded value was 6.1 x 10^{-8} and the lowest was 4.0 x 10^{-8} cm/sec. The steady to slowly decreasing permeability of SB mixture 2 indicates that there was no observable incompatibility between the SB and the Site groundwater, and also indicates a successful test result.

The pH and the electrical conductivity (EC) of the Site groundwater were measured at the beginning and end of the long-term permeability test, as recommended by ASTM D7100. The measured valves are shown in Table 9.

Table 9: EC and pH of Site Groundwater in Long-Term Permeability Test

	pH (units)	EC (micro-mhos/cm)
Initial – Influent	7.2	861
Initial – Effluent	7.2	5620
Final – Influent	7.9	818
Final – Effluent	7.4	5010

There was little significant change in either the pH or the EC during the long term test. The EC of the effluent is much more conductive than the influent. The increase in EC from influent to effluent indicates a typical adsorption of cations and anions across the specimen. Equilibrium is indicated when the effluent EC shows a stable value as shown in these results.

Conclusions

This laboratory testing program successfully demonstrated the low permeability and compatibility of the proposed soil-bentonite backfill mixture with the Site groundwater. The following conclusions may be drawn from these results:

- The available Site resources (trench spoil, Upper Lake water, and CAMU borrow soils) can be combined with imported bentonite clay to create the slurry and backfill for a slurry cutoff wall.
- API-grade bentonite clay is compatible with the Site groundwater.
- Portland cement is compatible with the Site groundwater.
- A mixture of at least 2% bentonite to a 50:50 mixture of trench spoil and CAMU borrow soils produces a workable and optimum mixture for a low permeability SB backfill.
- Long-term permeability testing shows that a SB mixture 2 is compatible with the Site groundwater.
- The long-term permeability testing of SB mixture 2 was measured at 4×10^{-8} cm/sec.
- Careful planning and execution of the work with comprehensive quality control and assurance is always recommended for slurry wall construction.

Please feel free to call me if you have any questions.

Sincerely,

Geo-Solutions Inc.

Steven R. Day
Vice President

Cc: Elaine Coombe, Shaw

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